Relationship Between Clinical Measurements and Motion of the First Metatarsophalangeal Joint During Gait*

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Abstract

Background: The range of joint motion is a commonly reported outcome measure in assessment of the great toe. Although motion of the first metatarsophalangeal joint during gait is of primary functional importance, clinicians rely on relatively static clinical measures to assess this joint. The relationship between the results of commonly used clinical tests of motion of the first metatarsophalangeal joint and motion of this joint during gait was assessed in a study of thirty-three subjects who had no history of a pathological condition of the foot or ankle.

Methods: An electromagnetic tracking device was used to acquire three-dimensional orientation data on the hallux with respect to the first metatarsal. Receivers were secured to the skin overlying the proximal phalanx of the hallux, the first metatarsal, and the medial aspect of the calcaneus. Measurements were recorded during four clinical tests. These tests assessed the active range of motion of the first metatarsophalangeal joint with the subject weight-bearing, the passive range of motion with the subject weight-bearing, the passive range of motion with the subject non-weight-bearing, and the motion during a heel-rise. The data collected with these tests were compared with motion of the first metatarsophalangeal joint during walking. The focus of the analysis was the dorsiflexion component of rotation.

Results: With the exception of the passive range of motion with the subject weight-bearing, the ranges of motion measured during all of the clinical tests exceeded the motion of the first metatarsal joint that is required during normal walking. The motion measured during heel-rise (r = 0.87, p < 0.001) and the active range of motion with the subject weight-bearing (r = 0.80, p < 0.001) had the strongest correlations with motion of the first metatarsophalangeal joint during gait. The mean dorsiflexion during the test of the active range of motion (44 degrees) was closer to the mean dorsiflexion during gait (42 degrees) than was the mean value measured during the heel-rise test (58 degrees). This study also demonstrated that the clinical tests are not interchangeable as their mean results differed by as much as 21 degrees.

Conclusions: The selection of a reliable and valid clinical test and an understanding of the relationship of the results of this test to the motion requirements during normal gait will help to standardize reporting techniques and will improve the ability of the clinician to determine the outcomes of treatment. This study showed that measurement of the active range of motion with the subject weight-bearing was a reliable and valid test and that the results were strongly correlated with motion of the first metatarsophalangeal joint during gait.

A critical component of normal walking is the achievement of adequate motion of the great toe, specifically dorsiflexion, during the terminal stance and preswing phases of gait. Restriction of motion of this joint can severely impair the function of the foot and can result in altered gait patterns and pathological changes in the joint. Clinical measurements of motion of the first metatarsophalangeal joint are used to guide decisions regarding treatment strategies that include the use of orthotics, modifications of footwear, and operative procedures. Additionally, these clinical measurements are a major component of clinical rating scales used to assess function of the foot.

Active and passive motion of the first metatarsophalangeal joint have been studied under static conditions in living subjects, in cadaver specimens, and during walking. The clinical measurements of motion in these investigations have varied substantially, with measurements of dorsiflexion ranging between 65 and 110 degrees and those of plantar flexion ranging between 23 and 45 degrees. There has been similar variability in the reported measurements of motion of the first metatarsophalangeal joint during gait, with values ranging between 50 and 90 degrees of dorsiflexion.

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The large range of reported values for motion of the first metatarsophalangeal joint may be related to a lack of standard measurement techniques. One of the main factors contributing to the discrepancy among the results of different investigations is related to the description of the zero, or starting, position for the measurement of joint motion. Measurement of motion of the first metatarsophalangeal joint referenced to the plantar plane of the foot results in values for dorsiflexion that are lower than those obtained when the measurement is referenced to the shaft of the first metatarsal (Fig. 1). Use of the metatarsal shaft as a reference takes into account the declination angle of the first metatarsal relative to the plantar plane of the foot. This declination angle varies according to the height of the arch.

Other factors that affect the results of measurement include the weight-bearing status during measurement, whether active or passive motion is being assessed, and the instrumentation and methods that are used to acquire the data. Many investigators have used clinical goniometry to obtain angular measurements of motion of the first metatarsophalangeal joint. This technique, while found to have acceptable intrarater reliability, may have questionable validity. Buell et al. reported a fair-to-good association between goniometric and radiographic measurements, but they did not provide correlation coefficients. Furthermore, those authors did not record goniometric and radiographic information simultaneously, and they did not use the same protocols for both types of measurements. An additional drawback to clinical goniometric techniques is the inability to assess motion during dynamic activities.

Two-dimensional imaging techniques have been used for dynamic measurements of motion of the first metatarsophalangeal joint. Potential errors in measurement with this type of analysis are due to out-of-plane motion and malalignment of anatomical segments that may cause distortion of angular data as they are projected onto the imaging plane. With the exception of Hopson et al., who excluded subjects who had foot progression angles of greater than 9 degrees, few investigators have addressed this issue when making measurements.

Although motion of the first metatarsophalangeal joint is of primary functional importance, it is difficult to measure during dynamic activities. Clinicians need to rely on relatively static clinical measures to assess motion of this joint. The relationship between the results of commonly used clinical tests of motion of the first metatarsophalangeal joint and motion of that joint during gait has not been established, to our knowledge. The purpose of the present study was to analyze this relationship. The selection of a reliable and valid clinical test and an understanding of the relationship of the results of this test to the motion required during normal gait will aid in the standardization of reporting methods and will improve the ability of clinicians to interpret clinical outcomes.

**Materials and Methods**

**Subjects**

Thirty-three subjects (fourteen women and nineteen men) between the ages of twenty and fifty-four years old (mean [and standard deviation], 28 ± 9.4 years old) participated in the current study. The subjects had no history of a pathological condition of the foot or ankle. In accordance with the policy of our university, all subjects were apprised of the requirements of participating

![Figure 2](image-url)
in the study, and informed consent was obtained. The university’s internal review board approved the study before collection of the data began.

Instrumentation

Motion of the hallux relative to the long axis of the first metatarsal was measured in three dimensions with use of the Flock of Birds electromagnetic tracking device (Ascension Technology, Burlington, Vermont). The six-degrees-of-freedom electromagnetic tracking device is capable of providing position and orientation values of small sensors with respect to a transmitter, within an operating range of 22.5 to 64.0 centimeters. This measurement system has been found to have excellent accuracy, with errors of 1.8 and 1.6 percent over the operating range, and resolution of 0.25 millimeter and 0.1 degree for position and orientation, respectively.

For testing, sensors were secured to the skin overlying the hallux, the first metatarsal, and the medial aspect of the calcaneus of the right foot. The sensor on the hallux was placed over the dorsomedial aspect of the proximal phalanx, medial to the tendon of the extensor hallucis longus. The sensor on the metatarsal was placed over the dorsomedial aspect of the metatarsal shaft, with avoidance of the abductor hallucis and the tendon of the extensor hallucis longus. The locations of the sensors were chosen in an effort to minimize the error introduced by movement of the skin and tendons over the underlying anatomical structures. In a recent study, use of these locations for the sensors resulted in a high degree of agreement between the motion detected by the sensors and the true underlying osseous movement. Mean differences of less than 1 degree were found between ranges of motion measured with skin-based and skeleton-based techniques.

Procedures

Motion of the hallux relative to the long axis of the first metatarsal (Fig. 1[a]) was measured during four clinical tests and during walking. The measurements, which will be described in detail, were made during an active range of motion with the subject weight-bearing, during a passive range of motion with the subject weight-bearing, during a passive range of motion with the subject non-weight-bearing, and during a heel-rise. Our rationale for using the heel-rise test was that it more closely simulates the functional weight-bearing position of the foot during the terminal stance phase of gait. The gait measurements were made as the subjects walked past the transmitter at a self-selected speed (Fig. 2).

A neutral, baseline position was measured while the subject stood on a smooth wooden platform with a comfortable base of support and his or her weight evenly distributed on both feet. For measurement of the active range of motion during weight-bearing, the subject stood with the toes extended over the edge of the platform, so that the metatarsal heads were supported but the platform did not interfere with motion of the first metatarsophalangeal joint. Position and orientation data were collected as the subject moved from a position of maximum plantar flexion to one of maximum dorsiflexion. For the assessment of the passive range of motion with weight-bearing, the subject maintained the just described position and one of us (D. A. N.) grasped the proximal part of the hallux and moved the first metatarsophalangeal joint through the range of maximum plantar flexion and dorsiflexion. The passive range of motion without weight-bearing was measured while the subject sat in a chair; the examiner held the ankle in the neutral (90-degree) position with one hand, grasped the proximal part of the hallux with the other hand, and then moved the metatarsophalangeal joint to the passive extremes of plantar flexion and dorsiflexion. The heel-rise test was performed while the subject was in a standing position. The subject was instructed to keep the entire hallux on the floor while lifting the ipsilateral heel as high as possible. Five trials were performed for each clinical test.

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TABLE I
INTRACLASS CORRELATION COEFFICIENTS AND
STANDARD ERRORS OF MEASUREMENT FOR TESTS OF MOTION
OF THE FIRST METATARSOPHALANGEAL JOINT

<table>
<thead>
<tr>
<th>Test</th>
<th>Intraclass $r$</th>
<th>Standard Error of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active range of motion with weight-bearing</td>
<td>0.99</td>
<td>1.46</td>
</tr>
<tr>
<td>Passive range of motion with weight-bearing</td>
<td>0.99</td>
<td>1.61</td>
</tr>
<tr>
<td>Passive range of motion with non-weight-bearing</td>
<td>0.99</td>
<td>1.77</td>
</tr>
<tr>
<td>Heel-rise</td>
<td>0.99</td>
<td>1.84</td>
</tr>
<tr>
<td>Walking</td>
<td>0.97</td>
<td>2.30</td>
</tr>
</tbody>
</table>

For the gait trials, the subject walked past the transmitter, with the examiner ensuring that the first complete step occurred within the optimum range of the transmitter. Three walking trials were performed by each subject. A pilot study of the motion of the metatarsophalangeal joint between consecutive steps revealed no difference between the first step and subsequent steps of twelve subjects. On the basis of this analysis, we thought that the first complete step adequately represented motion of the great toe during gait.

Data Analysis and Reduction

The electromagnetic tracking device provides position and orientation data for the sensors relative to the transmitter. Initial placement of the sensors on anatomical landmarks does not ensure their alignment with clinically relevant anatomical axes. To allow meaningful interpretation of the segment rotations, two transformation matrices were generated that related the assumed constant orientation of the sensors to the anatomically based local coordinate systems for the hallux ($T_h$) and first metatarsal ($T_m$) segments. This setup results in three mutually perpendicular axes embedded within each segment. The anatomically based local coordinate systems were defined by digitizing four noncollinear points on each segment with a calibrated stylus attached to one of the sensors. The resulting local coordinate systems had the positive y axis directed posteriorly within the long axis of the segment; the positive x axis was directed laterally; and the predominant direction of the positive z axis was inferior (Fig. 3).

Two additional transformation matrices ($R_{x/L}$ and $R_{y/L}$) were generated that related the local coordinate systems for the hallux and the first metatarsal to the global or laboratory coordinate system ($L$), centered in the transmitter. Finally, the anatomical orientation of the proximal part of the hallux relative to the first metatarsal ($R_{hm}$) was determined with the equation: $R_{hm} = [(R_{x/L} \times T_h)^T \times (R_{y/L} \times T_v)$. Descriptions of the angular orientation of the local coordinate system for the hallux were specified relative to an initial coincident alignment of the local coordinate system for the first metatarsal. Angular data for the hallux relative to the metatarsal were extracted from the transformation matrix ($R_{hm}$) with use of a Cardan angle system. A sequence of three ordered rotations (X-Z-Y) was used, which can be described by $\alpha$, $\beta$, and $\gamma$, representing dorsiflexion and plantar flexion, abduction and adduction, and medial and lateral rotation of the hallux relative to the first metatarsal, respectively. Data were collected at 100 hertz and filtered with use of a fourth-order digital filter (Butterworth) with a six-hertz cutoff frequency.

All angles are reported as the mean of the middle three (of the five) trials performed for each clinical test or as the mean of all three walking trials. Considering the predominant motion of the metatarsophalangeal joint during gait and the application of our findings to clinically based measures, we restricted the statistical analyses to the dorsiflexion-plantar flexion component of rotation (the x axis). Means, standard deviations, and standard errors of the mean were calculated for all reported variables. Intraclass correlation coefficients were calculated to provide an estimate of the degree of similarity among trials and an indication of trial-to-trial variability for the dependent variables. An analysis of variance was used to assess if the results of the clinical tests differed from each other. Follow-up comparisons were conducted with use of the Newman-Keuls test.

Graph showing the means and standard errors of the mean for dorsiflexion and plantar flexion during the clinical tests and walking trials for all subjects. PROMWB = passive range of motion with the subject weight-bearing, PROMNWB = passive range of motion with the subject non-weight-bearing, HR = heel-rise test, AROMWB = active range of motion with the subject weight-bearing, and WALK = walking trial.
Table II

Pearson Product-Moment Correlation Coefficients for Clinical Tests and Motion of the First Metatarsophalangeal Joint During Walking

<table>
<thead>
<tr>
<th>Test</th>
<th>Pearson r</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active range of motion with weight-bearing</td>
<td>0.80</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Passive range of motion with weight-bearing</td>
<td>0.61</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Passive range of motion with non-weight-bearing</td>
<td>0.67</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Heel-rise</td>
<td>0.87</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Pearson product-moment correlation coefficients were used to determine the relationship between the clinical measurements and motion of the first metatarsophalangeal joint during gait. A statistical power analysis was also performed to ensure a sample size that would provide sufficient protection from type-I errors. Given a sample size of thirty-three subjects and a level of significance of p < 0.05, we were able to detect significant differences with a power of 0.95.

Results

In the neutral, baseline position, the hallux was dorsiflexed a mean (and standard error) of 11 ± 1.4 degrees relative to the first metatarsal. The mean dorsiflexion of the hallux was 37 ± 2.8 degrees during the assessment of the passive range of motion with the subject weight-bearing, 44 ± 2.5 degrees during the assessment of the active range of motion with the subject weight-bearing, 57 ± 3.1 degrees during the assessment of the passive range of motion with the subject non-weight-bearing, and 58 ± 3.2 degrees during the heel-rise test. The mean dorsiflexion of the metatarsophalangeal joint in the sagittal plane during walking was 42 ± 2.3 degrees (Fig. 4).

An analysis of variance demonstrated significant differences between the results of the clinical tests (F = 37.3, p < 0.001). Post hoc comparisons showed that the motion measured during the heel-rise test and the passive range of motion with the subject non-weight-bearing did not differ from one another. The motion during the heel-rise differed from the active range of motion (p < 0.001) and from the passive range of motion with the subject weight-bearing (p < 0.001). The passive range of motion with the subject non-weight-bearing differed from both the active range of motion (p < 0.001) and the passive range of motion with the subject weight-bearing (p < 0.001). The active range of motion differed from the passive range of motion with the subject weight-bearing (p < 0.01). Intraclass correlation coefficients (3,3) were high, ranging between 0.97 and 0.99 (Table I). Standard error of measurement values were 2.3 degrees or less. The high degree of similarity between trials supported the use of mean data to represent the variables of interest in this study.

The Pearson product-moment correlation coefficients (range, 0.61 to 0.87) were significant (p < 0.001) for all correlations between the maximum dorsiflexion of the metatarsophalangeal joint during the clinical tests and that during walking (Table II). Motion of the first metatarsophalangeal joint during the heel-rise had the strongest relationship with that during walking (r = 0.87, p < 0.001), followed by the active range of motion with the subject weight-bearing (r = 0.80, p < 0.001). However, the mean value for the active range of motion with the subject weight-bearing (44 ± 2.5 degrees) was closer to that during walking (42 ± 2.3 degrees) than was the mean value during the heel-rise (58 ± 3.2 degrees).

Discussion

Clinical measurements of motion of the first metatarsophalangeal joint are an essential component guiding decisions regarding treatment and assessments of clinical outcome. These measurements are also a major part of clinical rating scales used to assess function of the foot. A review of the literature reveals the wide variability in normative values reported for standard measurements of motion of the first metatarsophalangeal joint. This variability is a source of confusion for clinicians attempting to ascertain and restore normal motion of the joint. Furthermore, the relationship between these clinical measures and motion of the first metatarsophalangeal joint during gait has not been previously reported, to our knowledge.

The focus of the present investigation was on the relationship between dorsiflexion of the first metatarsophalangeal joint as measured with commonly used clinical tests and this motion during gait. The four selected tests reflect the spectrum of measurements typically used in the clinical arena. Two of the clinical tests, the heel-rise test (r = 0.87, p < 0.001) and the assessment of the active range of motion with the subject weight-bearing (r = 0.80, p < 0.001), were found to provide results that strongly correlated with motion of the first metatarsophalangeal joint during gait. Measurement of the active range of motion with the subject weight-bearing may be a more appropriate choice for a clinical test because the mean value for dorsiflexion (44 ± 2.5 degrees) more closely matched that during gait (42 ± 2.3 degrees) than did the mean value for the heel-rise test (58 ± 3.2 degrees).

With the exception of the passive range of motion with the subject weight-bearing, the values for motion of the first metatarsophalangeal joint measured during these clinical tests exceeded the motion that is necessary for normal walking. Our findings are consistent with those of Hopson et al., who also reported greater values for motion of the first metatarsophalangeal joint when subjects were assessed while in a non-weight-bearing position rather than in a weight-bearing position. The increased motion of the first metatarsophalangeal joint when subjects are non-weight-bearing has been attrib-
uted to unrestricted plantar flexion of the first metatarsal, which produces a change in the location of the transverse axis from within the center of the head of the first metatarsal to a more proximal and dorsal position. This mechanism allows the hallux to glide and rotate without impaction on the first metatarsal head. The heel-rise test allows for similar plantar displacement of the first metatarsal as the hallux is stabilized against the ground. The value for dorsiflexion during the heel-rise test (58 ± 3.2 degrees) was comparable with the value for passive dorsiflexion with the subject non-weight-bearing (57 ± 3.1 degrees).

Similar to the study by Hopson et al., our study also showed that the clinical tests are not interchangeable. The choice of one test over another could considerably affect the outcome scores of a clinical examination in which measurements of range of motion are used as indicators of function of the foot. With the exception of the data provided by the heel-rise test and the assessment of the passive range of motion with the subject non-weight-bearing, the motion data derived from the clinical tests differed from each other. The mean dorsiflexion values from the weight-bearing and non-weight-bearing assessments of passive motion differed by as much as 21 degrees. These findings emphasize the need for consistency in methods of assessment and for documentation of the clinical tests that are chosen for measurement of the first metatarsophalangeal joint, particularly in follow-up and repeated-motion assessments.

It is interesting to note that the values in our study were lower than those reported in previous investigations, in which similar static tests and analyses of motion during gait were used. These differences may be due, in part, to differences in instrumentation and measurement techniques. The choice of a reference position aligned with the metatarsal shaft instead of the plantar plane of the foot takes into account the potential variability in the declination angle among different arch heights. Previously reported values for this angle have ranged between 15 and 45 degrees. The declination angle may also affect measurements of mean dorsiflexion. In our study, the neutral position represented the angle between the metatarsal and the plantar surface of the hallux and was found to be 11 ± 1.4 degrees. This neutral position, which is comparable with the declination angle, was found to be moderately predictive of the dorsiflexion achieved during trials involving active motion, heel-rise, and walking (r = 0.60, 0.61, and 0.74, respectively). These findings reflect the variety of foot types in the current investigation.

We believe that the techniques for data collection that were used in the present study resulted in greater accuracy of measurement of motion of the metatarsophalangeal joint. The use of the electromagnetic tracking device allowed direct measurement of the orientation of the hallux relative to the first metatarsal during both static and dynamic tests. Three-dimensional data collection techniques were used to extract the planar motion data about the x axis, minimizing error associated with out-of-plane rotations. The methods that were used in the current study were validated in a previous investigation involving cadaver, in which the mean values derived with skin-based and skeleton-based measurement techniques differed by less than 1 degree.

The current study demonstrated a correlation between the motion of the first metatarsophalangeal joint as measured with commonly used clinical tests and that required during normal walking. Functional activities such as stair-climbing, squatting, and reaching may require additional motion. Greater motion is also needed for certain sports. The relationship between motion during these activities and that measured with current clinical tests has not been established, to our knowledge.

References